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Quarks, Astrophysics and Space Physics

Dynamical Parton Energy Loss in Relativistic Heavy Ion Collisions

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Outline:

- Jet tomography
    - Jet quenching
    - Jet acoplanarity
- Hydro+jet model
- Results
    - Suppression factor
    - Correlation function
- Summary

Collaborator:

Yasushi Nara (Univ. of Arizona)

Reference:

T.Hirano and Y.Nara,
Phys. Rev. C **66**, 041901(R) (2002).

Introduction

Recent important hadronic observables in high p_T regions at Relativistic Heavy Ion Collider (RHIC)

1. Suppression of the yields
2. Disappearance of back-to-back correlations

⇓

The diagnostic tools for dence matter (Quark Gluon Plasma?)

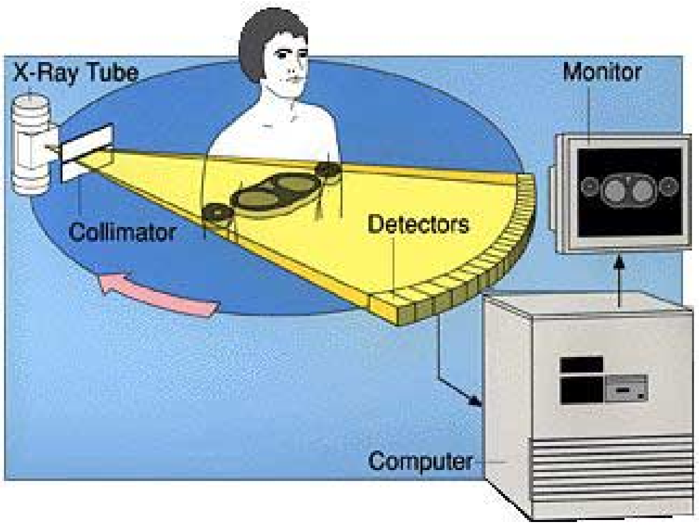
"jet tomography"

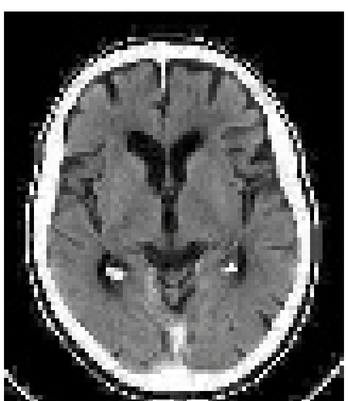
Jet Tomography

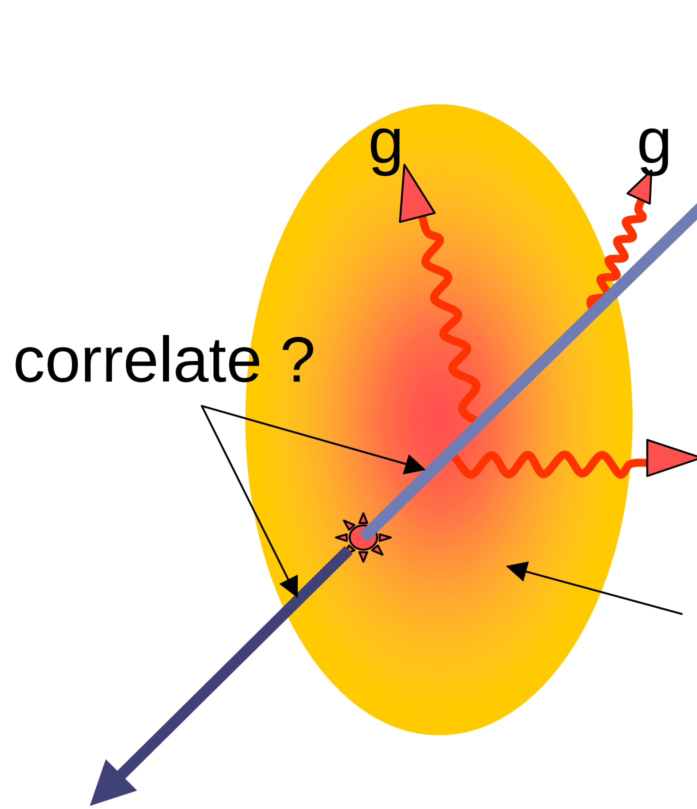
Gyulassy, Plummer ('90)

Tool 1. Jet quenching

CT (computed tomography) scan







Hot matter produced in a collision

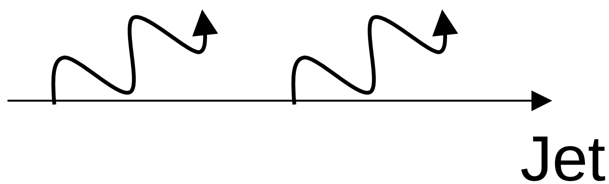
Tool 2. Jet acoplanarity
(transverse momentum imbalance)

Bjorken('82)
Appel ('86)
Blaizot
McLerran ('86)

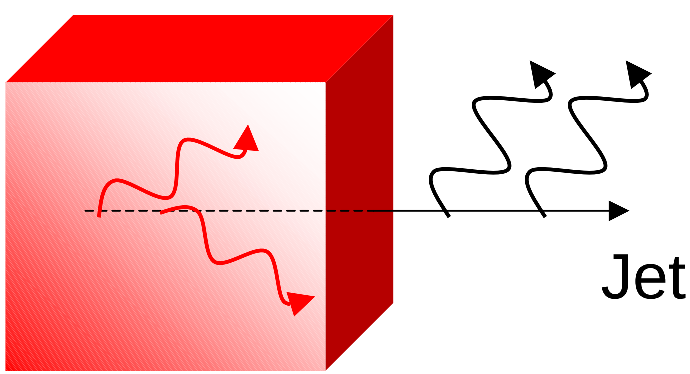
Figures taken from M.Gyulassy's presentation

Tool 1. Jet Quenching

In vacuum



In hot (deconfined) matter



Nucleon-nucleon collisions

Energy loss in vacuum (~fragmentation)

$$-dE/dx \approx \kappa \approx 1\,\mathrm{GeV/fm}$$

κ: string tension

Nucleus-nucleus collisions

Additional energy loss in matter

$$-\Delta E \sim \alpha_s \sqrt{E_{cr} E} \quad \text{for } E < E_{cr}$$

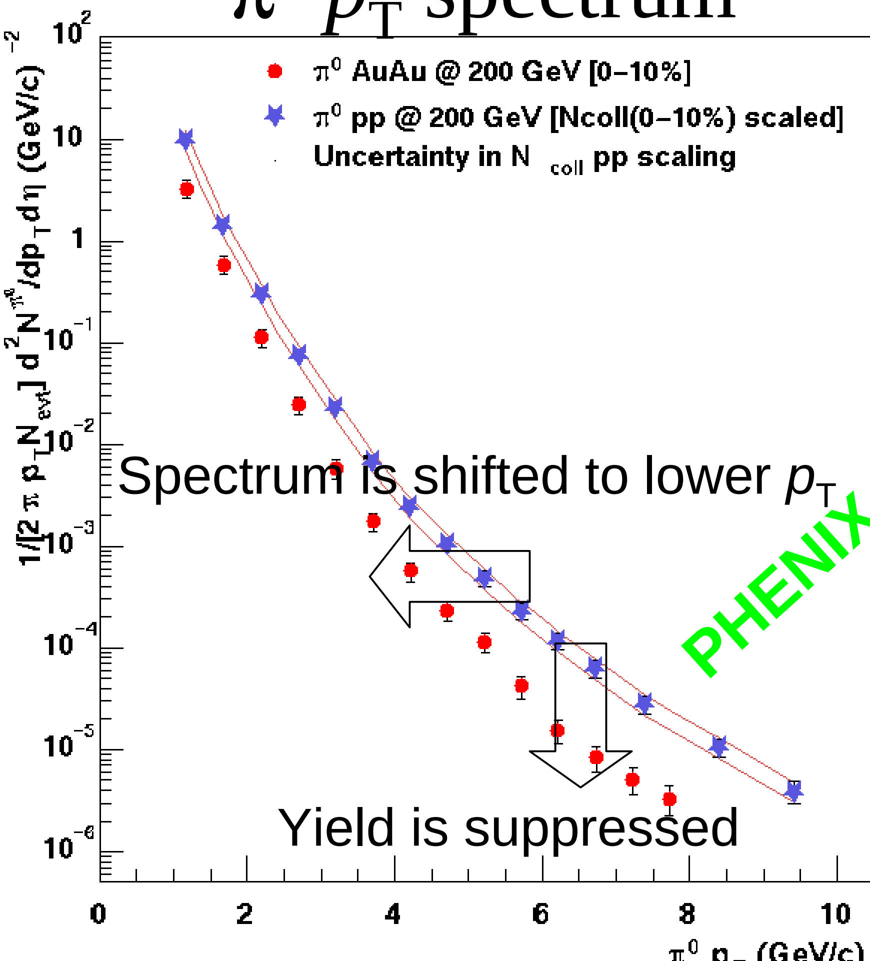
$$\sim \alpha_s E_{cr} \quad \text{for } E > E_{cr}$$

where $E_{cr} = \mu^2 L^2 / \lambda$ Baier *et al.*, (1997)

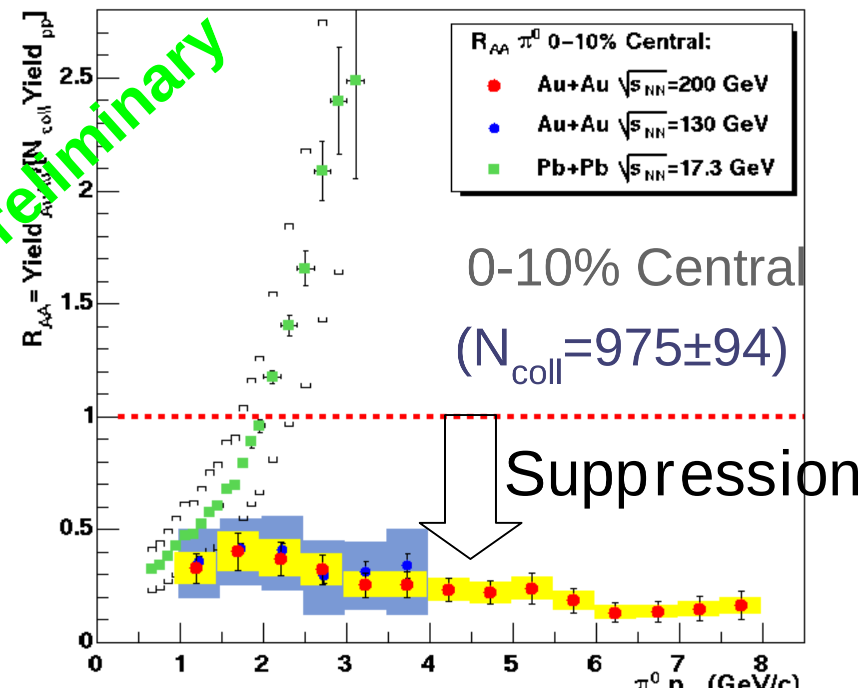
Tool 1. Jet Quenching (contd.)

Suppression Factor by PHENIX

$\pi^0\ p_T$ spectrum



$$R_{AA}(p_T) = \frac{d^2N^{\mathrm{A+A}}/dp_T d\eta}{\langle N_{\mathrm{coll}}\rangle d^2N^{\mathrm{N+N}}/dp_T d\eta}$$

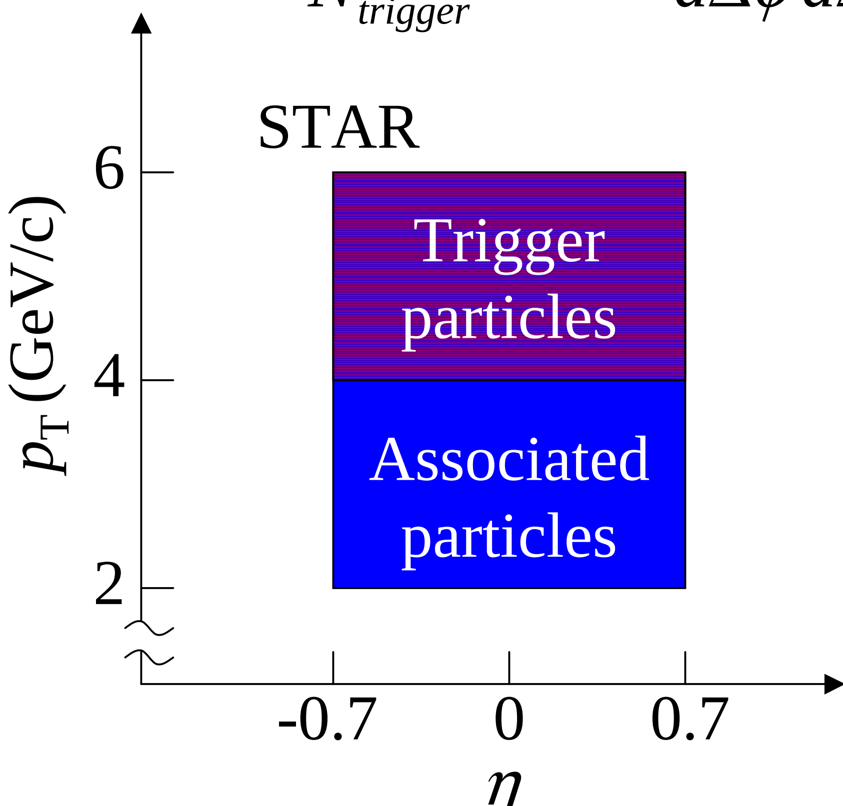


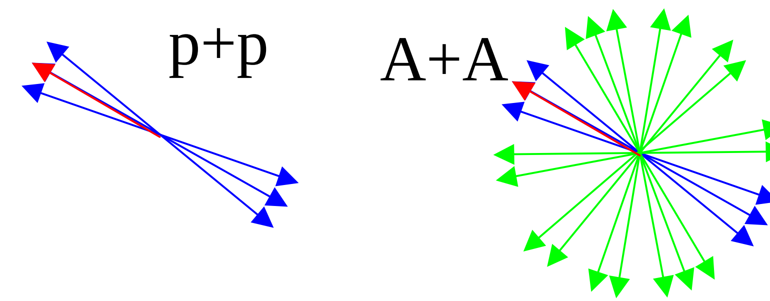
From D. d'Enterria, talk at QM2002.

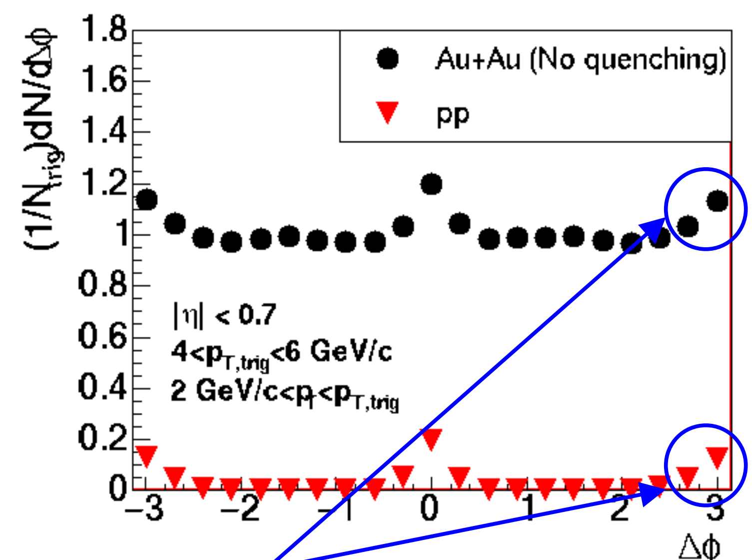
Tool 2. Jet Acoplanarity

Back-to-back correlations of high p_T hadrons

$$C_2(\Delta\phi) = \frac{1}{N_{trigger}} \int d\Delta\eta \frac{dN}{d\Delta\phi\, d\Delta\eta}$$



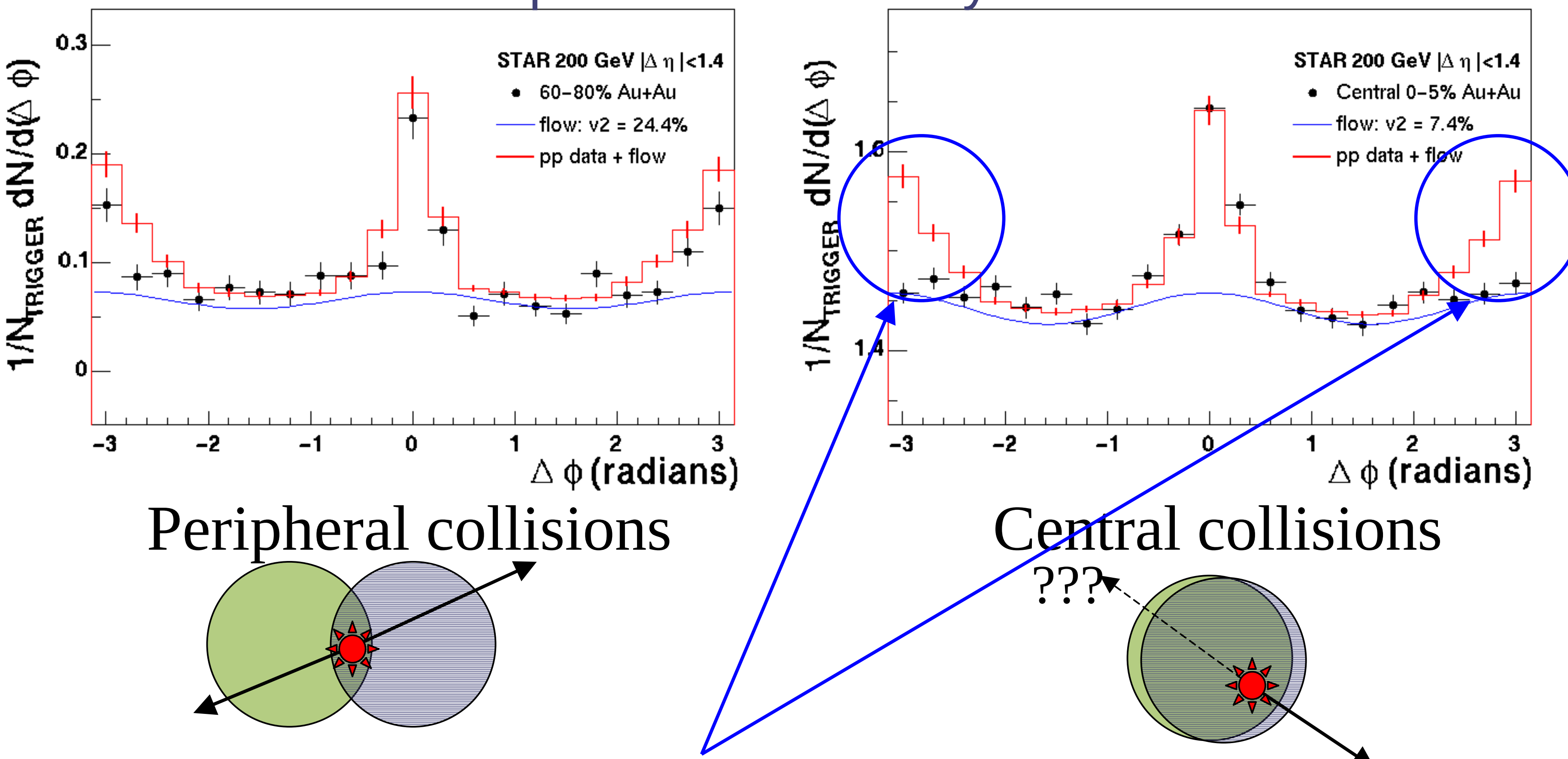




Strength of away-side peaks
are the same in no jet quenching case

Tool 2. Jet Acoplanarity (contd.)

Experimental Data by STAR



Disappearance of away-side peaks!

From D.Hardtke (STAR), talk at QM2002.

Model

- Jet quenching
- Jet acoplanarity

Interplay between soft and hard is *important!*

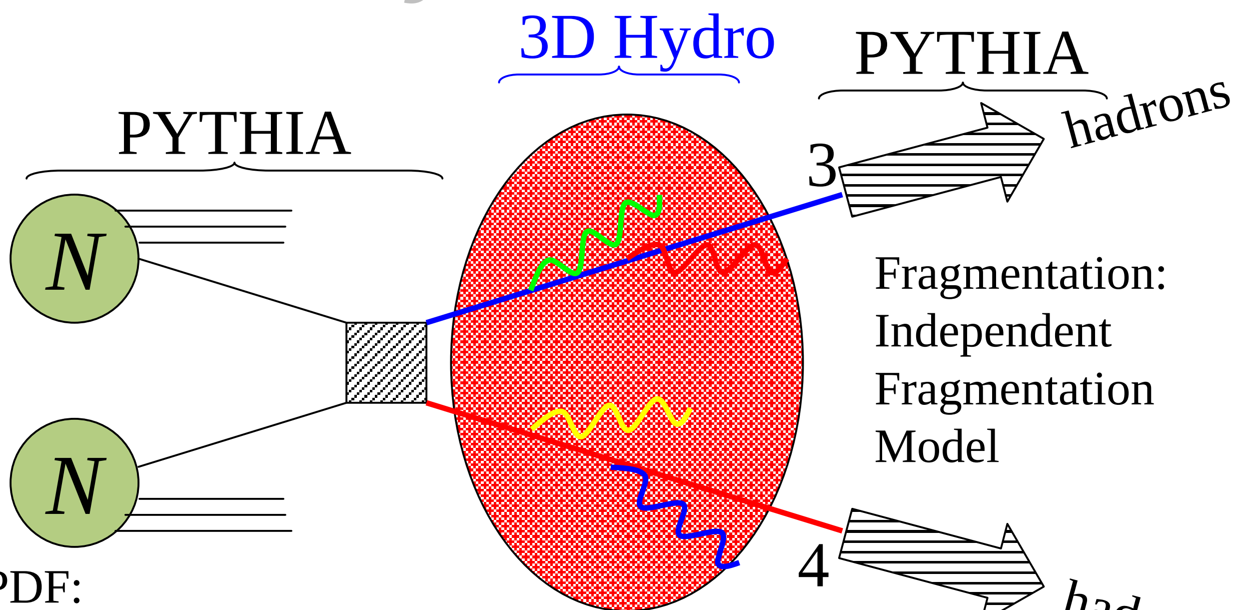
Hydro + Jet model

Soft (hydrodynamics)
- Space-time evolution of matter
- Phase transition between QGP and hadrons
- Particle spectra in low p_T region

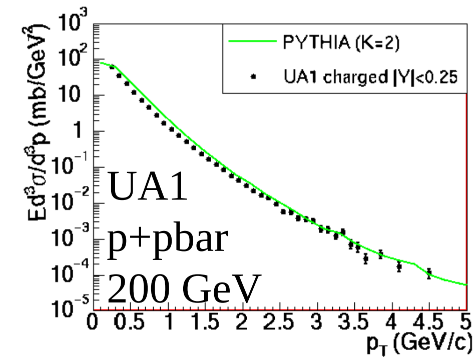
Hard (mini-jets)
- Production of (mini-)jets
- Propagation through fluid elements
- Fragmentation into hadrons

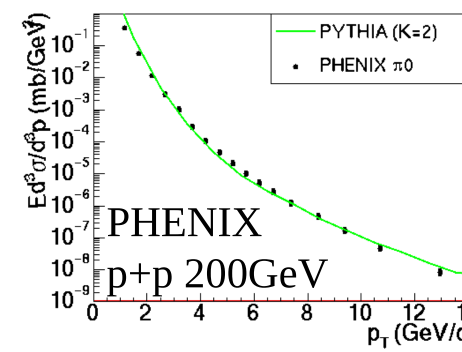
Interaction between fluids and mini-jets through parton energy loss

The Hydro+Jet Model



Fragmentation:
Independent
Fragmentation
Model





PDF:
Collinear: CTEQ5LO
k_T: Gaussian
$\langle k_T^2 \rangle = 1\mathrm{GeV}^2/c^2$

Parton energy loss: dE/dx
(I will discuss later…)

pQCD LO:

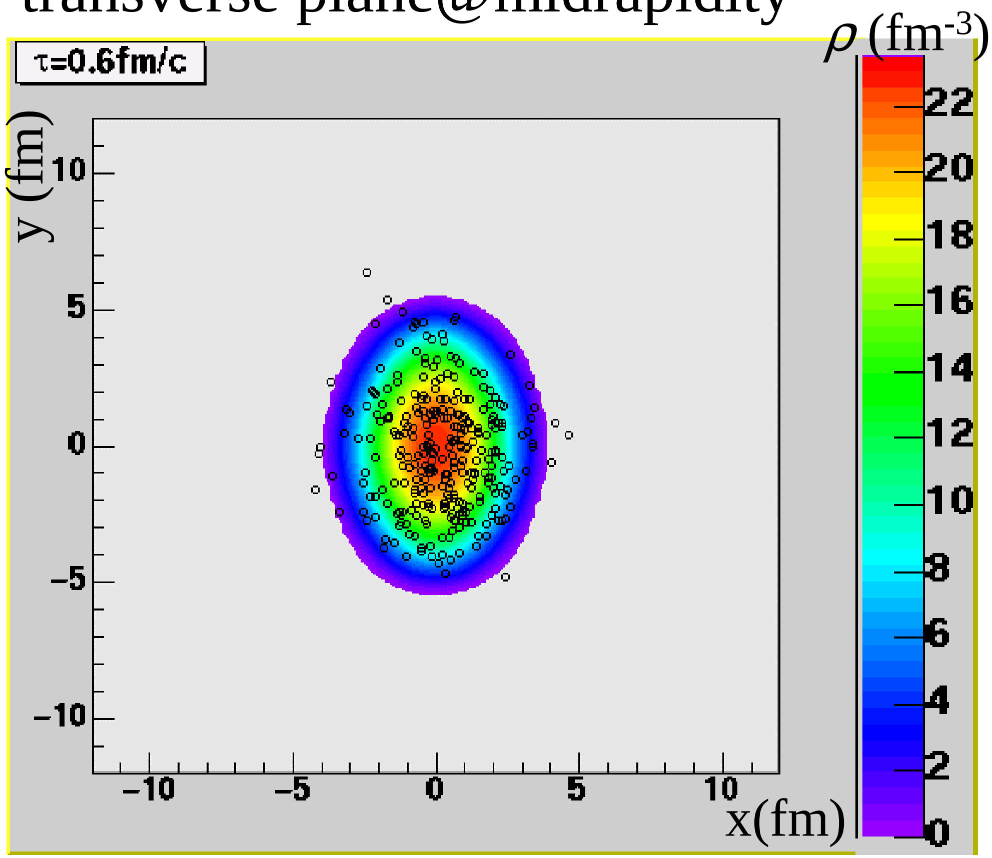
$$q+q' \rightarrow q+q', q+\bar{q} \rightarrow q'+\bar{q}'$$
$$q+\bar{q} \rightarrow g+g, q+g \rightarrow q+g$$
$$g+g \rightarrow q+\bar{q}, g+g \rightarrow g+g$$

$$E\frac{d\sigma^{pp}_{\text{jet}}}{d^3p} = K\sum_{ab}\int g(k_{T,a})k_{T,a}dk_{T,a}\, g(k_{T,b})k_{T,b}dk_{T,b} \times \int f_a(x_1,Q^2)dx_1 f_b(x_2,Q^2)dx_2 E\frac{d\sigma^{ab\rightarrow cd}}{d^3p}$$

*Initial and final state radiation are included.

Jets and Hydro Evolution in the Transverse Plane

Au+Au 200*A*GeV, *b*=8 fm
transverse plane@midrapidity



Gradation
→ *Themalized* parton density
Plot (open circles)
→ Mini-jets (p_T>2GeV/c)

•Initial configuration of mini-jets
→Prop. to # of binary collisions
•Assuming jets move along straight paths
(eikonal approximation)

Parton Energy Loss

M.Gyulassy *et al*. (2000)

•Coherent model

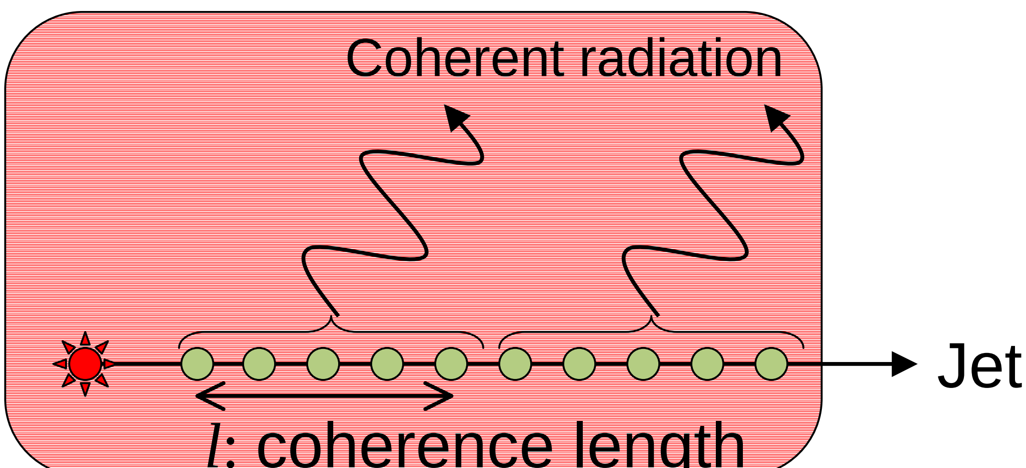
Position of a jet

$$\Delta E = -\underline{C}\int_{\tau_0}^{\infty}(\tau-\tau_0)\underline{\rho(\tau,\overline{x(\tau)})}\log\left(\frac{2E}{\mu^2 L}\right)$$

Adjustable parameter

Parton density
from hydrodynamic
simulations

Initial enegy
of a jet



Landau-Pomeranchuk
-Migdal effect
~Destructive interference
of radiation

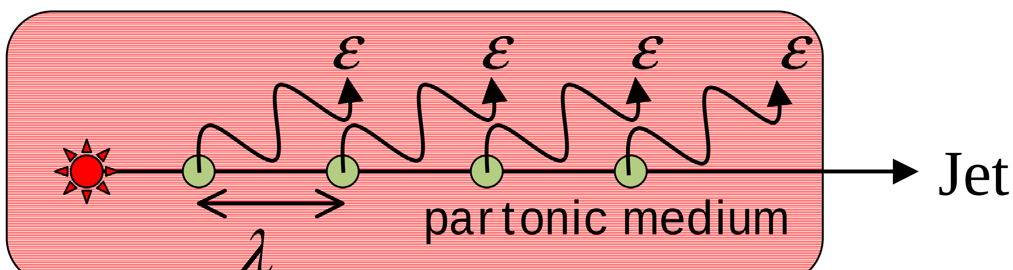
Parton Energy Loss (contd.)

- Incoherent model

$$\frac{dE}{dx} = -\frac{\varepsilon}{\lambda} = -\varepsilon\sigma\rho\left(\tau, x(\tau)\right)$$

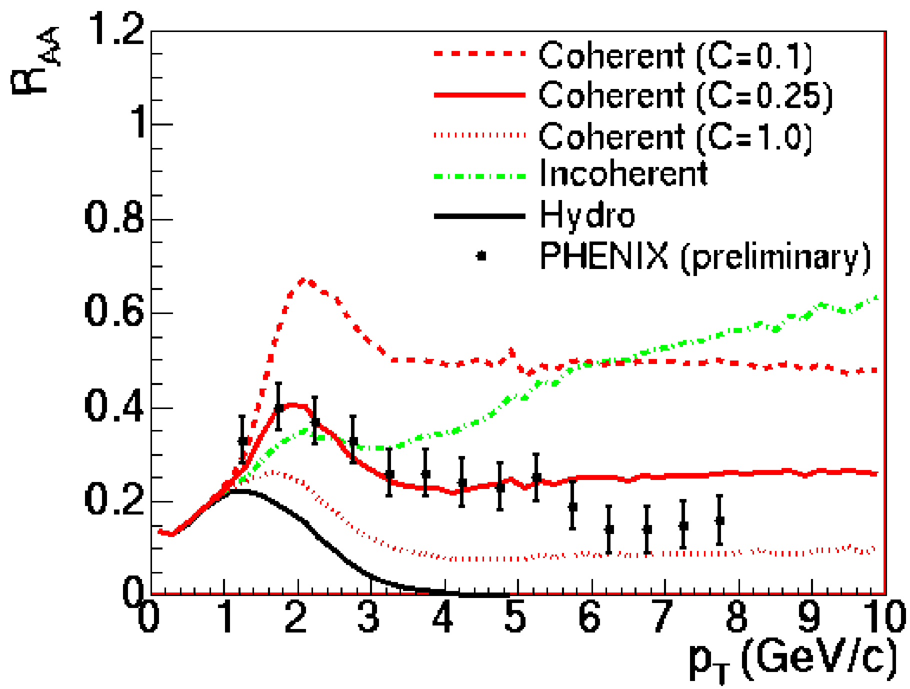
Mean free path

Adjustable parameter



Total incoherent energy loss
→The sum of single scattering

Suppression Factor



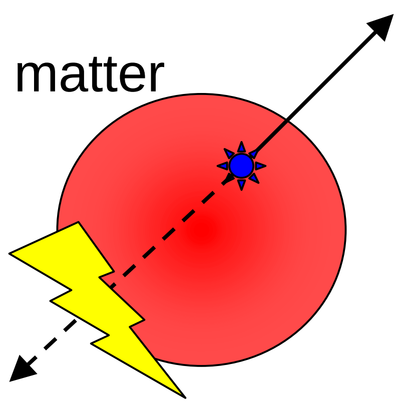
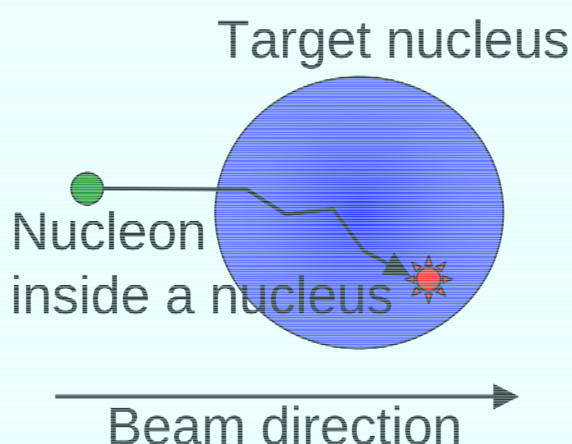
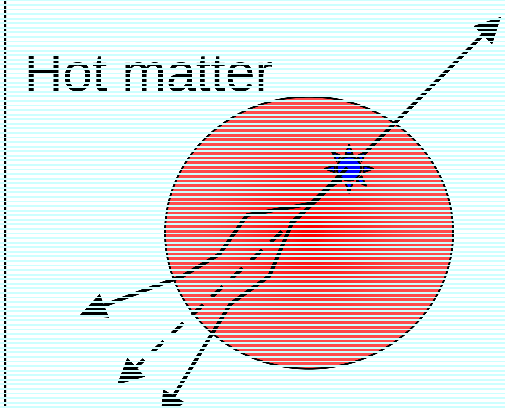
$$R_{AA}(p_T) = \frac{d^2N^{A+A}/dp_T d\eta}{\langle N_{coll}\rangle d^2N^{N+N}/dp_T d\eta}$$

Data from D. d'Enterria, talk at QM2002.

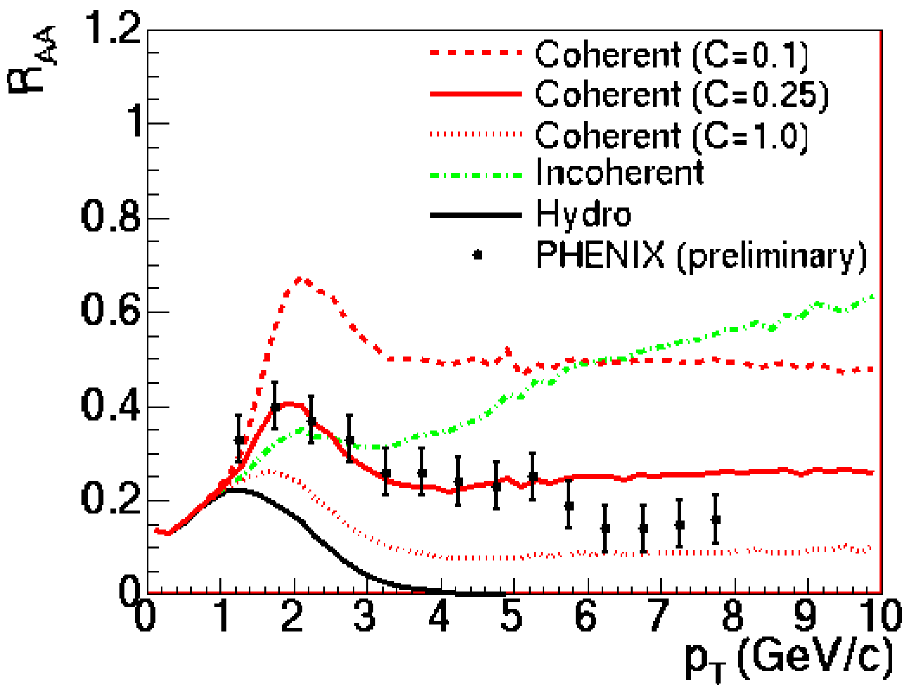
- Coherent model
  →Almost flat
- Incoherent model($\varepsilon\sigma$=0.06)
  →Increase with p_T
- Experimental data
  →Gradually decrease

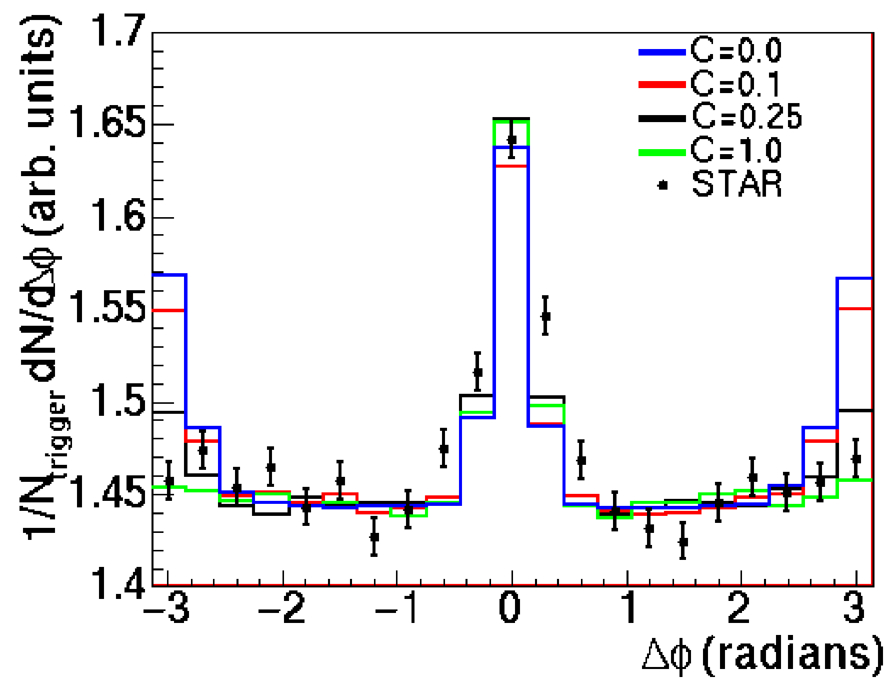
The coherent model with *C*=0.25 quantitatively reproduces the data below p_T~6 GeV/c

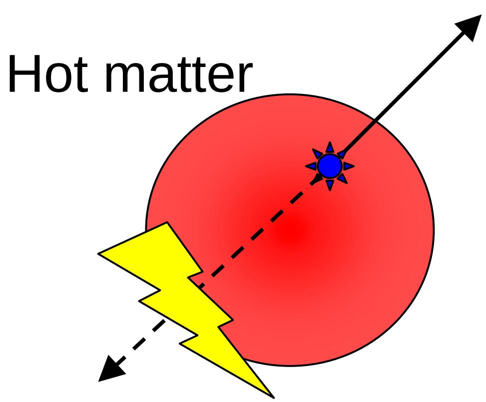
Three Possible Effects on Back-to-back Correlations

1.Energy loss of jets	2. Primordial k_T of initial partons	3. Broadening of jets
Final state	Initial state	Final state
 Absorption	 “Cronin effect”	 Random walk behavior

1. Effect of Parton Energy Loss

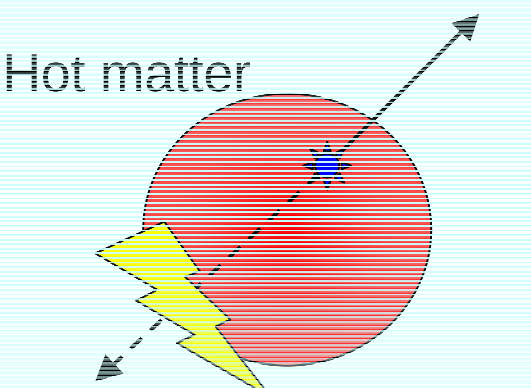
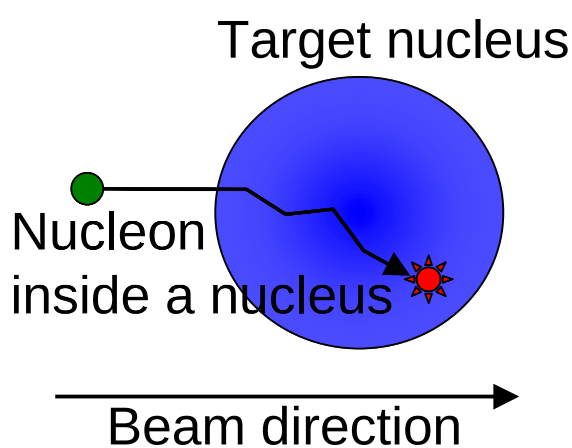
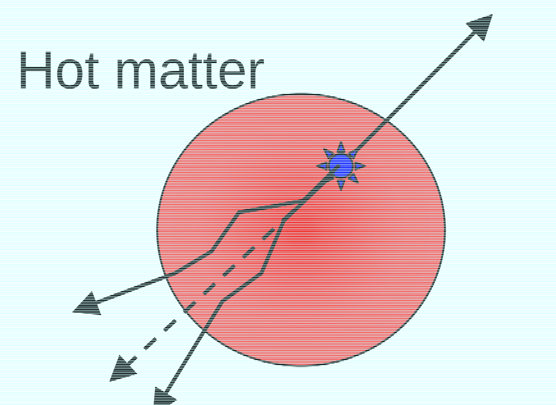




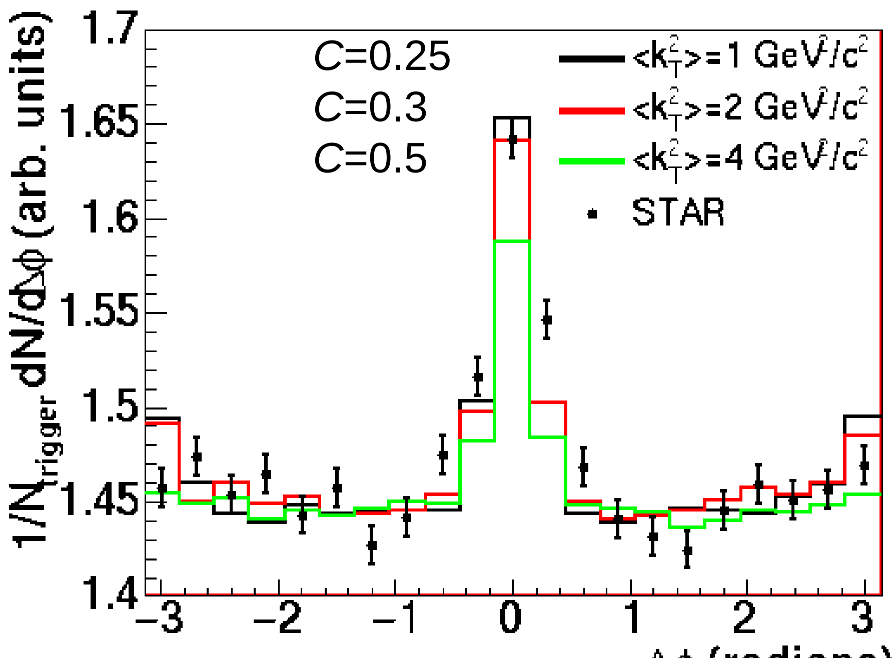


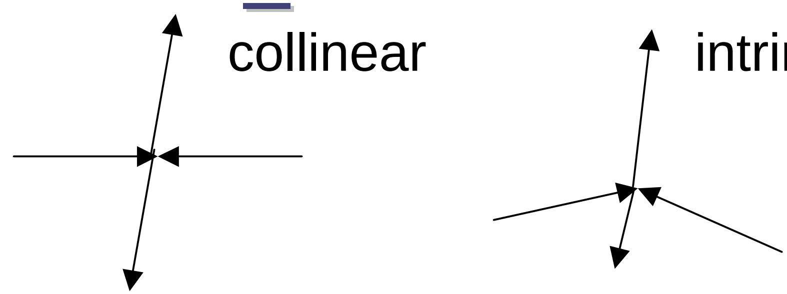
Simultaneous reproduction of R_{AA} and C_2 ?
→Another mechanism is needed!

Three Possible Effects on Back-to-back Correlations

1.Energy loss of jets	2. Primordial k_T of initial partons	3. Broadening of jets
Final state	Initial state	Final state
 Absorption	 “Cronin effect”	 Random walk behavior

2. Effect of Intrinsic k_T



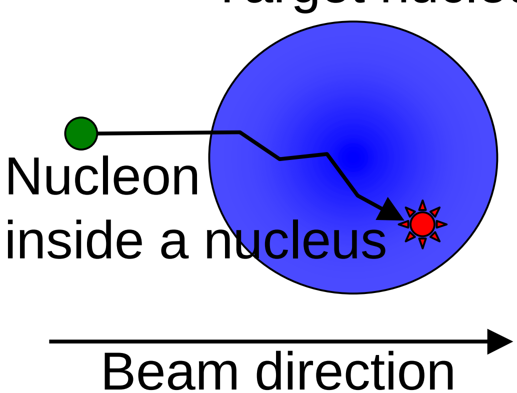


Primordial k_T distribution

$$g(k_T) \propto \exp(-k_T^2/\sigma_T^2)$$

$$\langle k_T^2 \rangle = \sigma_T^2 = 1, 2 \text{ or } 4\,\text{GeV}^2/c^2$$

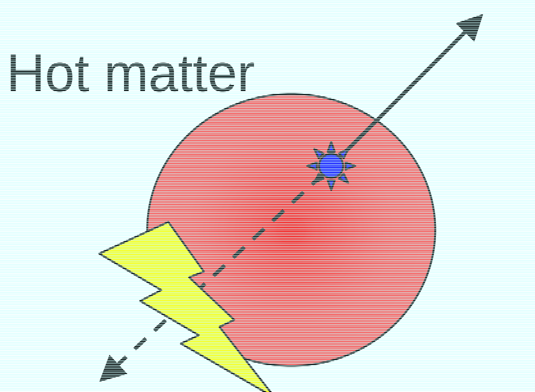
$$\langle k_T^2 \rangle \sim 2\,\text{GeV}^2/c^2\ \text{@SPS}$$



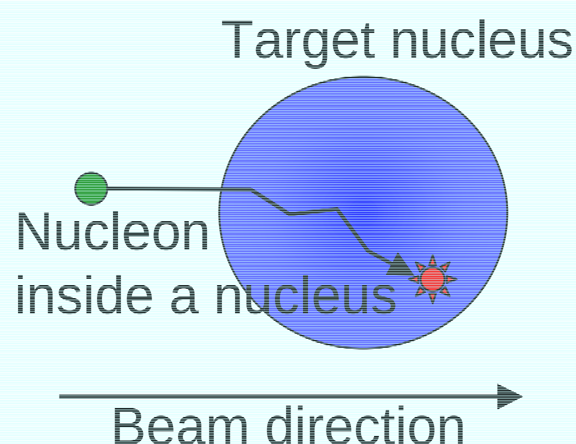
Intrinsic k_T is insufficient to the disappearance of back-to-back correlation!

Three Possible Effects on Back-to-back Correlations

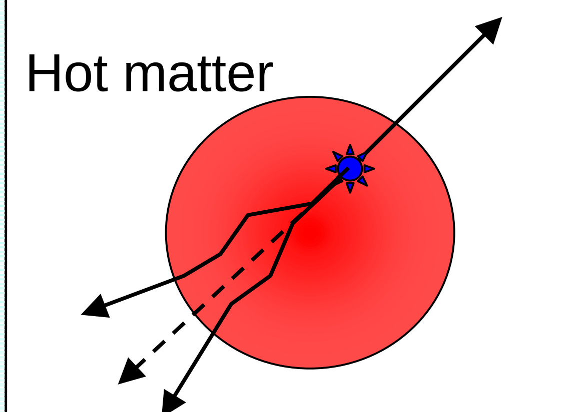
1.Energy loss of jets	2. Primordial k_T of initial partons	3. Broadening of jets
Final state	Initial state	Final state



Absorption

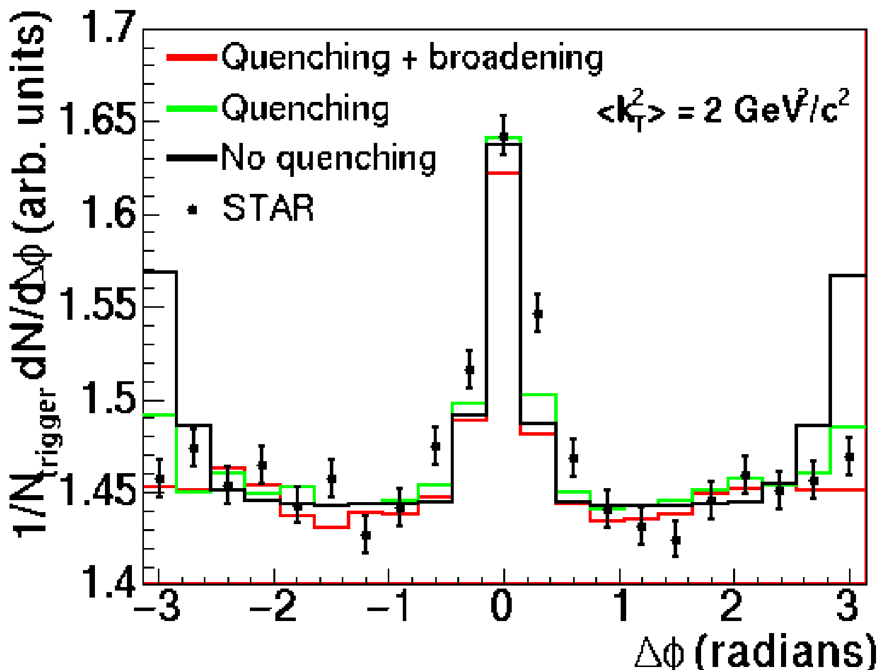


“Cronin effect”



Random walk behavior

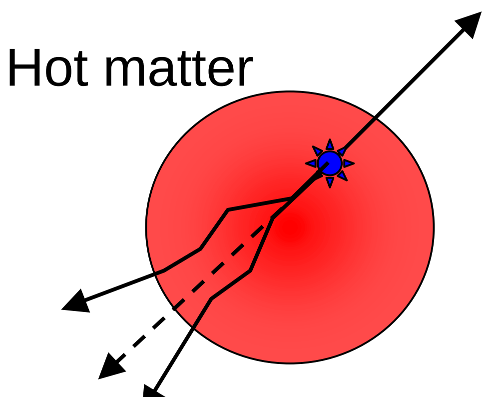
3. Effect of Broadening



$$\left\langle p_\perp^2 \right\rangle = (\alpha_s N_c / 4)^{-1} |dE / dx|$$

$p_\perp$: Transverse momentum orthogonal to its direction of motion

R.Baier *et al*., (1997)



Reduction of the away-side peaks:
~60% from parton energy loss & intrinsic k_T
~40% from broadening

Summary

- The hydro+jet model for analyzing high p_T regions in relativistic heavy ion collisions
  - **Suppression factor**
    - Coherent model with C=0.25 quantitatively reproduces the data below p_T~6 GeV/c
    - How do we obtain the decreasing R_{AA} ?
  - **Back-to-back correlations**
    - All three effects (energy loss, intrinsic k_T, and broadening) are responsible for disappearance of back-to-back correlations.